ELSEVIER

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Energy Procedia 37 (2013) 6125– 6132

Energy Procedia

GHGT-11

Evaluating the Suitability for CO_2 Storage at the FutureGen 2.0 Site, Morgan County, Illinois, USA

Alain Bonneville[1]*, Tyler Gilmore[1], Charlotte Sullivan[1], Vince Vermeul[1], Mark Kelley[2], Signe White[1], Delphine Appriou[1], Bruce Bjornstad[1], Jacqueline Gerst[2], Neeraj Gupta[2], Jake Horner[1], Caitlin McNeil[2], Mark Moody[2], Williams Rike[2], Frank Spane[1], Paul Thorne[1], Evan Zeller[2], Fred Zhang[1], Jeffrey Hoffmann[3], Kenneth Humphreys[4]

[1]Pacific Northwest National Laboratory, Richland, WA 99352, USA
[2] Battelle, Columbus, Ohio, USA
[3]National Energy Technology Laboratory, Pittsburgh, PA, USA
[4]FutureGen Industrial Alliance Inc., Washington, DC, USA

Abstract

FutureGen 2.0 site will be the first near-zero emission power plant with fully integrated long-term storage in a deep, non-potable saline aquifer in the United States. The proposed FutureGen 2.0 CO_2 storage site is located in northeast Morgan County, Illinois, U.S.A., forty-eight kilometres from the Meredosia Energy Center where a large-scale oxy-combustion demonstration will be conducted. The demonstration will involve > 90% carbon capture, which will produce more than one million metric tons (MMT) of CO_2 per year. The CO_2 will be compressed at the power plant and transported via pipeline to the storage site. To examine CO_2 storage potential of the site, a 1,467m characterization well (FGA#1) was completed in December 2011. The target injection zone for CO_2 storage is in a zone of high permeability within the upper portion of the Mt. Simon Sandstone. Confining beds of the overlying Eau Claire Formation reach a thickness of 126 m. Characterization of the target injection zone and the overlying confining zone was based on wellbore data, cores, and geophysical logs, along with surface geophysical (2-D seismic profiles, magnetic and gravity), and structural data collected during the initial stage of the project . Based on this geological model, 3D simulations of CO_2 injection and redistribution were conducted using STOMP-CO2, a multiphase flow and transport simulator. After this characterization stage, it appears that the injection site is a suitable geologic system for CO_2 sequestration and that the injection zone is sufficient to receive up to 33 MMT of CO_2 at a rate of 1.1 MMT/yr.

Keywords: carbon sequestration, CO_2 geological storage, brine aquifer, Illinois, Mt Simon sandstone

* Corresponding author. Tel.: +1-509-371-7263; fax: +1-509-371-7150.
E-mail address: alain.bonneville@pnnl.gov

doi:10.1016/j.egypro.2013.06.541

1. The FUTUREGEN 2.0 project

In September 2010, the FutureGen Alliance signed a Cooperative Agreement with the United States Department of Energy (DOE) to partner in the development of FutureGen 2.0, a large-scale oxy-combustion repowering project that will use carbon capture and storage (CCS) technology. The FutureGen 2.0 Project is a public-private partnership, with costs shared by DOE and the other project partners. DOE has awarded $1 billion in American Recovery and Reinvestment Act funding for the project through its demonstration (cost-share) phase.

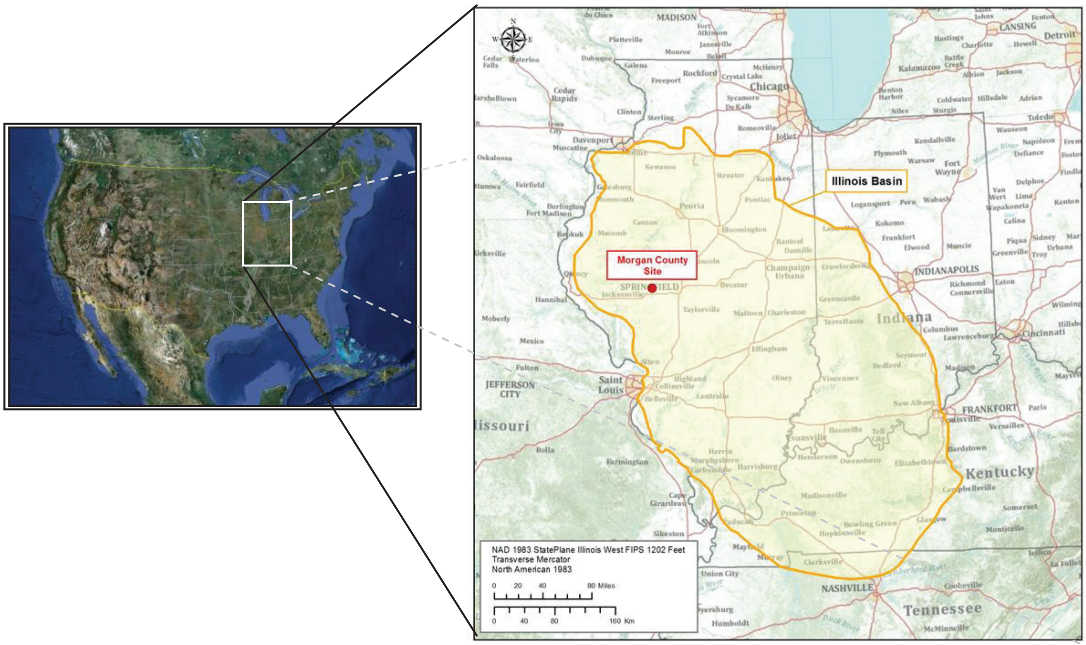

Figure 1. The Illinois Structural Basin Within the Midwestern United States (modified from [1])

Pursuant to the Cooperative Agreement, the FutureGen Alliance is working with Ameren Energy Resources (Ameren), Babcock & Wilcox Company, and Air Liquide Process and Construction, Inc. to develop a near-zero emission, coal-fueled power plant. The Alliance plans to acquire a portion of Ameren's existing Meredosia Power Plant in Meredosia, Illinois, and repower one of its units with oxy-combustion and carbon capture technology. The oxy-combustion boiler, air separation unit, and CO_2 purification and compression unit will allow the plant to capture more than 90 percent of its CO_2 emissions and reduce other emissions to near zero.

The captured CO_2 will be transported from the power plant through an underground pipeline to injection wells located on a single well pad in Morgan County, Illinois, 18 km northeast of the City of Jacksonville (Figure 1). We present in this paper a scenario based on four horizontal injection wells, which is one of the final design configurations under considerations along with other more conventional vertical well designs. The wells will be drilled into the Mount Simon Sandstone, a formation that underlies whole central Illinois and would serve as a permanent underground CO_2 storage reservoir (Figure 2). As much as 1.1 MMT of CO_2 may be injected annually and over 30 years, a total of up to 33 MMT will be injected. Visitor, research, and training facilities located near the CO_2 storage site will provide public education and outreach, as well as training and research opportunities associated with CO_2 capture and storage.

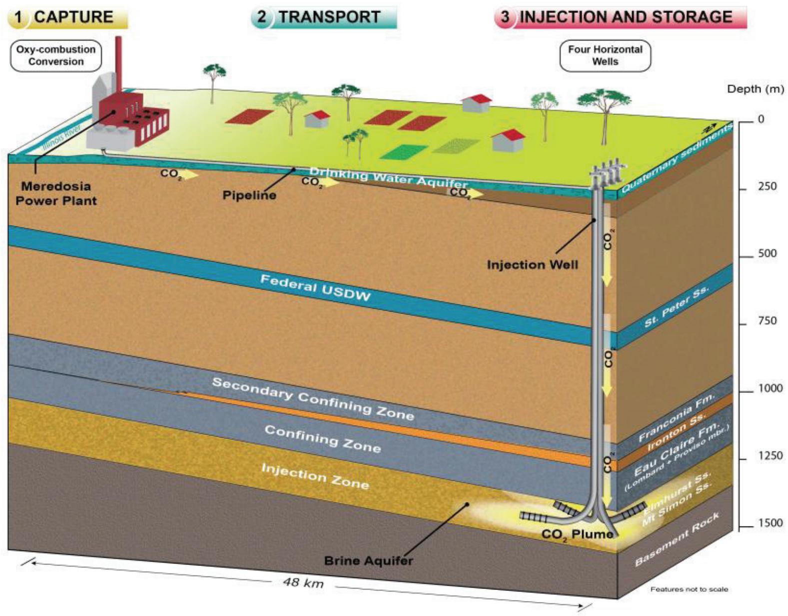

Figure 2. Graphical Overview of the Conceptual Design of the FutureGen 2.0 CO_2 Storage Site

At the Meredosia power plant, the CO_2 will be dehydrated, processed for removal of contaminants, and compressed to 14.5 Mpa before entering the pipeline. At these conditions, the CO_2 will be in a dense supercritical fluid phase and non-corrosive. The estimated length of the pipeline to the injection well site is 48 km.

An injection permit application has been prepared, and once permitted, the injection wells will be constructed at the site (Figure 2). Each well will be designed to provide operational flexibility and backup capability. The surface facilities will mainly consist of a site control building housing the major operational components of the CO_2 pipeline and storage site and a well annulus pressure maintenance and monitoring system building.

CO_2 will be injected into a zone of high permeability within the upper portion of the Mt. Simon Sandstone (Figure 2). The proposed injection zone consists of quartz sandstone, and it has demonstrated reservoir capacity in natural-gas storage facilities elsewhere in the Illinois Basin. The injection zone contains a hyper saline aquifer with a temperature of approximately 39.4°C and total dissolved solids of 47,500 mg/L, well in excess of recommended US Safe Drinking Water Act standards. The injection zone is overlain by the Eau Claire Formation, a thick regional confining zone with low permeability above the Elmhurst Sandstone member. The Franconia Dolomite and Davis member serves as a secondary confining zone for additional protection of underground sources of drinking water (USDW).

The present paper presents the results of the first stage of this project that consisted in the characterization of the storage site and in the study of the CO_2 plume behavior.

2. Site Characterization

2.1. Geological context

Structural dips on sedimentary strata within the western part of the Illinois Basin are low—generally less than one degree to the east and southeast, based on regional structure maps. The geologic structure in the vicinity of the proposed Morgan County CO_2 injection site consists a very gentle, 0.25-deg dip to the southeast. The principal geologic structure in proximity to Morgan County is the very broad Sangamon Arch. Neither these maps nor any other published sources [2, 3] indicate the existence of any mapped faults or fracture zones in the vicinity of the proposed Morgan County CO_2 injection site.

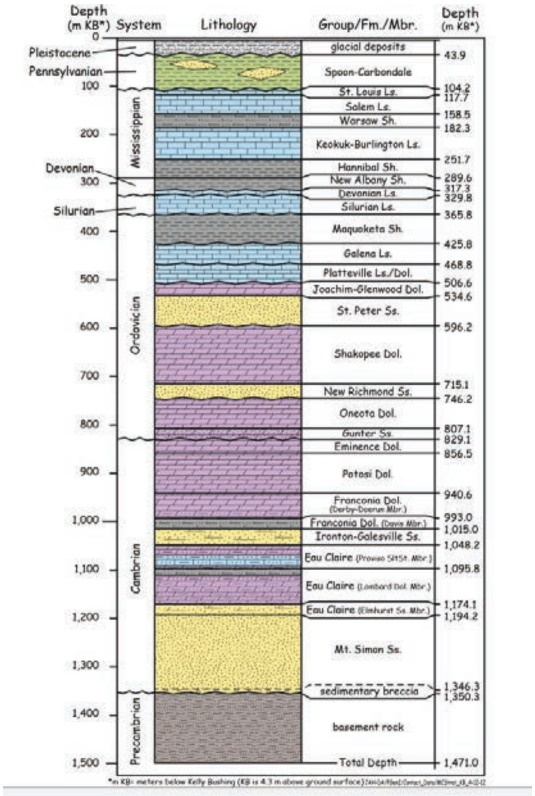

Figure 3. Stratigraphic Column for the Stratigraphic Well at the Proposed Morgan County CO_2 Injection Site. Wavy lines represent major unconformities reported for the Morgan County area by Willman [4].

Two, two-dimensional (2D) surface seismic lines, were acquired in January 2011 along public roads near the proposed Morgan County CO_2 injection site. Both profiles indicate a thick sequence of Paleozoic-aged rocks. Although the seismic lines are not of optimal quality due to seismic noise, they do not indicate the presence of faults or large changes in thickness of the injection or confining zones. A site-specific surface gravity survey was also conducted in 2011, including 240 regularly spaced stations within a 2-mi by 2-mi area that covers the characterization well site and the proposed injection site. The survey results have a good correlation with the regional gravity maps of Daniels et al. [5] and show some positive gravity anomalies that could be linked to the presence of paleo-relief on the Pre-Cambrian basement rocks. The gravity survey does not indicate any major subsurface discontinuities within the site.

2.2. The stratigraphic well

To support the evaluation of the Morgan County site as a potential carbon storage site a deep stratigraphic well was drilled in December 2011 1.6 km east of the planned injection site.

The stratigraphic well reached a total depth of 1,471 m bgs within the Precambrian basement. The well penetrated 146 m of the Eau Claire formation and 156 m of the Mount Simon sandstone. Contact picks in the stratigraphic well (Figure 3) are based on correlations with wells in the Illinois State Geological Survey database as well as comparison of the well cuttings with lithologies in drillers logs and published descriptions.

The stratigraphic well was extensively characterized, sampled, and geophysically logged during drilling. These data, together with the regional data form the basis for developing a conceptual model. A total of 55 m of whole core were collected from the lower Eau Claire-upper Mount Simon Sandstone and 10.5 m were collected from lower Mount Simon Sandstone-Precambrian basement interval. In addition to whole drill core, a total of 130 side-wall core plugs were obtained from the combined interval of the Eau Claire Formation, Mount Simon Sandstone, and the Precambrian basement (Figure 4).

2.3. Injection Zone

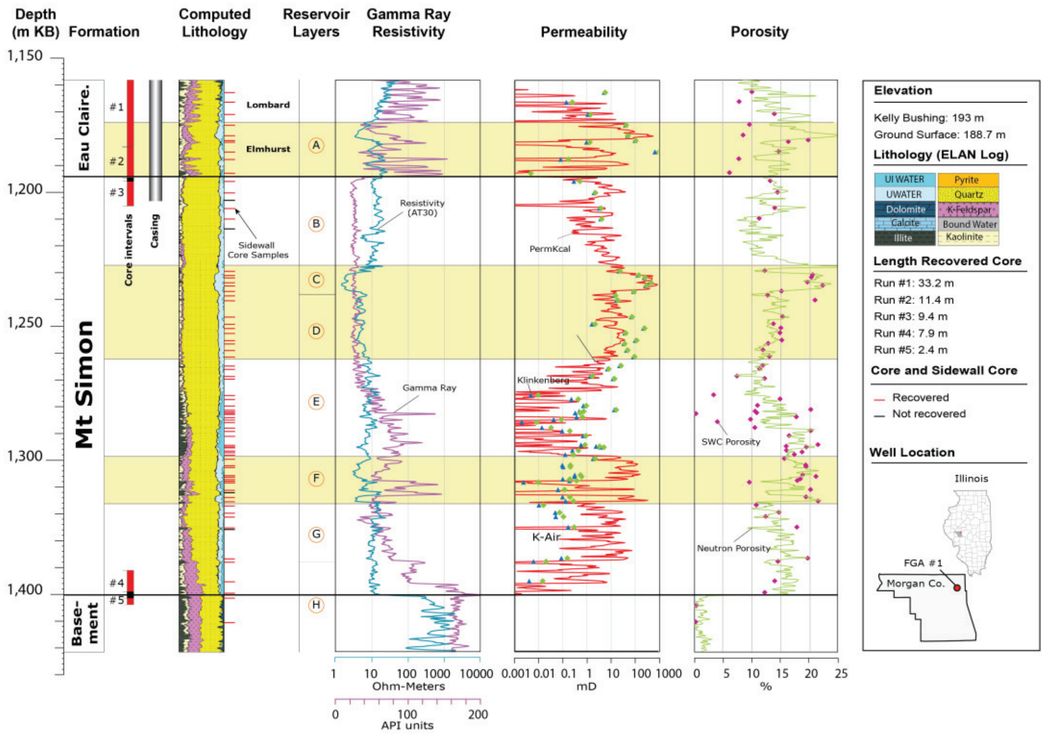

Figure 4. Lithology, Mineralogy, and Hydrologic Units of the Proposed Mount Simon Sandstone Injection Zones within the Stratigraphic Well. See text for explanations.

The thickness of the proposed injection zone is 156 m at the stratigraphic well (Figure 4). As observed in cuttings, core and image logs, the Mount Simon Sandstone primarily consists of fine-to-coarse quartz arenite with local granule-rich quartz or arkosic sandstone beds. Based on the computed mineralogy deduced from the ELAN log, feldspar appears to be considerably more common in the lower part of the

Mount Simon Sandstone. The interpreted mineralogy and lithology based on well-log signatures in the stratigraphic well is presented in Figure 4. Cored intervals are indicated with red bars, rotary side-wall core, and core plug locations are indicated to the right of the computed lithology panel. Standard gamma ray and resistivity curves are shown in the second panel; ELAN-calculated permeability (red curve) and magnetic resonance-based permeability (black curve) are in the third panel, along with two different lab measurements of permeability for each rotary side-wall core.

Neutron- and density-crossplot porosity is shown in the fourth panel, along with lab-measured porosity for core plugs and rotary side-wall cores, the average porosity for the reservoir is 10% and zones with higher permeabilities, and higher expected potential for injectivity are highlighted. Permeability in the sandstones, as measured in rotary side-wall cores and plugs from whole core, appears to be dominantly related to grain size and abundance of clay. Ratios of vertical to horizontal permeabilities (Kv/Kh) were successfully determined for 20 vertical/horizontal core-plug pairs.

2.4. Confining Zone

The Proviso and Lombard members of the Eau Claire Formation form the primary confining zone for the proposed Morgan County CO_2 injection site. The combined thickness of these strata is 126 m at the stratigraphic well. 24 m of whole core were obtained in the Lombard member of the Eau Claire Formation, along with 13 rotary side-wall cores. In addition, 10 rotary side-wall cores were collected in the Proviso member.

Rock cuttings and rotary side-wall core lithologies from the upper Proviso member include tan to light brown, dense, occasionally glauconitic microcrystalline, slightly dolomitic limestone. Thinly bedded to laminated siltstone and mudstone dominate lithologies in the Lombard. The permeabilities of the rotary side-wall cores in the Proviso range from 0.000005 mD to 1 mD. Permeabilities in the Lombard member range from 0.001 mD to 28 mD, reflecting the greater abundance of siltstone in this interval, particularly in the lowermost part of the member.

3. Simulation of CO_2 injection

A stratigraphic conceptual model of the geologic layers from the Precambrian basement to ground surface was constructed based on the geologic setting and site characterization data. Several simulations of CO_2 injection and plume displacement have then been performed.

Physical processes modeled in the reservoir simulations included non-isothermal multi-fluid flow and transport for a number of components (e.g., water, salt, and CO_2) and phases (e.g., aqueous and gas). The preliminary reservoir model assumes isothermal conditions, which are appropriate if the temperature of the injected CO_2 is similar to the formation temperature. Reservoir salinity is considered in the simulations because salt precipitation can occur near the injection well in higher permeability layers as the rock dries out during CO_2 injection. Mineralization reactions, iron carbonate precipitates in sandstone and dewatering of clays in shales, are not considered due to the absence of precise information; laboratory investigations are currently quantifying the importance of these reactions at the Morgan County site.

All the numerical simulations were executed using the STOMP-CO2 simulator [6, 7]. Partial differential conservation equations for fluid mass, energy, and salt mass compose the fundamental equations for STOMP-CO2. A fully coupled well model in STOMP-CO2 was used to simulate the injection of $ScCO_2$ under a specified mass injection rate, subject to a pressure limit. The three-dimensional, boundary-fitted numerical model grid was designed to have constant grid spacing with higher resolution in the area influenced by the CO_2 injection (5 x 5 km^2), with increasingly larger grid spacing moving out in all lateral directions toward the domain boundary.

Then, injection into four lateral wells with a well-bore radius of 11.4 cm was modeled, with the lateral leg of each well being located within the best layer of the injection zone to maximize injectivity. The CO_2 mass injection rate was distributed among the four injection wells for a total injection rate of 1.1 MMT/yr during 30 years. The injection rate was assigned to each well proportional to the well's lateral length. A maximum injection pressure of 15.5 Mpa, which is only 3.1 Mpa above ambient formation pressure, was assigned at the top of the screened interval. This scenario was simulated for a total time of 100 years to predict the migration of CO_2 and formation fluids. Figure 5 shows the mass of injected CO_2 over time, demonstrating that the injection rate of 1.1 MMT/yr can be attained with the four lateral injection wells. Most of the CO_2 mass occurs in the super-critical phase, with just over 18 percent occurring in the dissolved phase at the end of the simulation period. Note that residual trapping begins to take place once injection ceases, resulting in about 12 percent of the total CO_2 mass being immobile at the end of 100 years.

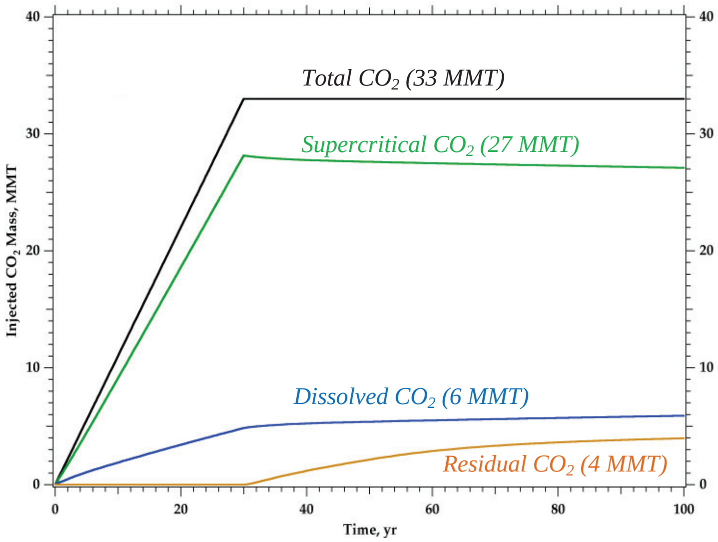

Figure 5. Mass of Injected CO_2 over Time Integrated over the Entire Model Domain.
CO_2 mass includes both free (mobile) and trapped (immobile) gas mass.

Most of the CO_2 resides in the Mount Simon Sandstone. A small amount of $ScCO_2$ enters into the Elmhurst and the lower part of the primary confining zone (Lombard). When injection ceases at 30 years, the lateral growth becomes negligible but the plume continues moving slowly primarily upward. Once CO_2 reaches the low-permeability zone in the upper Mount Simon it begins to move laterally. There is no additional $ScCO_2$ entering the confining zone from the injection zone after injection ceases.

4. Monitoring Program

An extensive monitoring program is being developed: to track the lateral extent of CO_2 within the target injection zone; to verify that it is effectively contained; to characterize any geochemical or geomechanical changes that occur within the injection zone and overlying confining zones; to assure permanency of storage; and last to validate that there are no negative surface impacts. The proposed monitoring program includes hydraulic, geophysical, and geochemical components for characterizing the complex fate and transport processes of CO_2 injection. The injection wells and monitoring wells will be monitored over the duration of the project to characterize pressure and CO_2 transport response and guide operational and regulatory decision making. These monitoring results, along with those from a deep early-detection monitoring well installed just above the primary confining zone, are designed to detect any early, unexpected upward migration across the primary confining zone. The monitoring program will adopt both direct and indirect monitoring methodologies for assessing CO_2 fate and transport within and adjacent to the injection zone. Multiple indirect methods will be evaluated and screened throughout the design and initial injection testing phase of the project to identify the most promising monitoring technologies under site specific conditions. Screening criteria will include 1) data quality, 2) implementability, 3) cost effectiveness, and 4) landowner/public interests. Direct monitoring and protection of underground source of drinking water (USDW) is required by the regulator and is a primary objective of this monitoring program. In addition to USDW monitoring, other surface and near-surface monitoring approaches include soil-gas monitoring, atmospheric monitoring, and ecological monitoring.

Summary

The completion of reservoir characterization at the Morgan County site is an important milestone in the life of the FutureGen project, which plans to inject more than one million metric tons of CO_2 per year beginning in 2017. At the end of this stage, it appears that the injection site is a suitable geologic system for CO_2 sequestration and that the injection zone is sufficient to receive up to 33 MMT of CO_2 at a rate of 1.1 MMT/yr.

Acknowledgements

The FutureGen 2.0 project is supported by a $1 billion commitment in U.S. federal funding from the American Recovery and Reinvestment Act. The program is implemented under Cooperative Agreement DE-FE0001882 between the U.S. Department of Energy and the FutureGen Industrial Alliance, a non-profit membership organization created to benefit the public interest and the interests of science through research, development, and demonstration of near-zero emissions coal technology. Members of the Alliance include some of the largest coal producers, coal users, and coal equipment suppliers in the world. For more information on FutureGen 2.0, please visit www.futuregenalliance.org.

References

[1] Buschbach, T.C. and D.R. Kolata, *Regional setting of Illinois Basin*, in *Interior Cratonic Basins*, K.D. Leighton MW, Oltz DF, and Eidel JJ Editor. 1991, American Association of Petroleum Geologists Tulsa, Oklahoma. p. 20-55.

[2] Whiting, L.L. and D.L. Stevenson, *The Sangamon Arch*. 1965: State of Illinois, Department of Registration and Education, Illinois State Geological Survey.

[3] Kolata, D.R. and W.J. Nelson, *Tectonic history of the Illinois Basin*, in *Interior Cratonic Basins*, K.D. Leighton MW, Oltz DF, and Eidel JJ Editor. 1991, American Association of Petroleum Geologists Tulsa, Oklahoma, USA. p. 263-285.

[4] Willman, H.B., *Handbook of Illinois stratigraphy*. 1975: Illinois State Geological Survey.

[5] Daniels, D.L., R.P. Kucks, and P.L. Hill, *Illinois, Indiana, and Ohio magnetic and gravity maps and data*, in *A website for distribution of data: U.S. Geological Survey Data Series 321*. 2008.

[6] White, M.D. and M. Oostrom, *STOMP Subsurface Transport Over Multiple Phases, Version 4.0, User's Guide*. 2006, Pacific Northwest National Laboratory: Richland, Washington,USA.

[7] White, M.D., D.H. Bacon, B.P. McGrail, D.J. Watson, S.K. White, and Z.F. Zhang, *STOMP Subsurface Transport Over Multiple Phases: STOMP-CO2 and STOMP-CO2e Guide, Version 1.0*. 2012, Pacific Northwest National Laboratory: Richland, Washington, USA.